

Development of fetal hearing

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Abstract

Previous research has revealed that the human fetus responds to sound, but to date there has been little systematic investigation of the development of fetal hearing. The development of fetal behavioural responsiveness to pure tone auditory stimuli (100 Hz, 250 Hz, 500 Hz, 1000 Hz, and 3000 Hz) was examined from 19 to 35 weeks of gestational age. Stimuli were presented by a loudspeaker placed on the maternal abdomen and the fetus's response, a movement, recorded by ultrasound. The fetus responded first to the 500 Hz tone, where the first response was observed at 19 weeks of gestational age. The range of frequencies responded to expanded first downwards to lower frequencies, 100 Hz and 250 Hz, and then upwards to higher frequencies, 1000 Hz and 3000 Hz. At 27 weeks of gestational age, 96% of fetuses responded to the 250 Hz and 500 Hz tones but none responded to the 1000 Hz and 3000 Hz tones. Responsiveness to 1000 Hz and 3000 Hz tones was observed in all fetuses at 33 and 35 weeks of gestational age, respectively. For all frequencies there was a large decrease (20–30 dB) in the intensity level required to elicit a response as the fetus matured. The observed pattern of behavioural responsiveness reflects underlying maturation of the auditory system. The sensitivity of the fetus to sounds in the low frequency range may promote language acquisition and result in increased susceptibility to auditory system damage arising from exposure to intense low frequency sounds.

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There is now little doubt that the ability to respond to sound commences in the prenatal period,^{1 2} however, there have been few systematic investigations of hearing in the fetus and thus the development of fetal auditory abilities remains largely unknown.³ Fetal auditory system functioning may only be studied indirectly by the observation of a behavioural response to a sound stimulus.⁴ Techniques of auditory evoked brainstem responses or evoked otoacoustic emissions, which may directly assess auditory function, cannot be applied during the prenatal period. As such, investigations of fetal hearing provide direct evidence of auditory thresholds for behavioural responsiveness and only indirect, by inference, evidence of absolute auditory thresholds (this issue will be returned to later). The following paper examines the very early development of behavioural responsiveness to auditory tones,

that is, in the prenatal period, and may provide information on the functioning and maturation of the auditory system. Two aspects of fetal auditory responsiveness are examined: the range of frequencies responded to and the intensity required to elicit a response ('sensitivity') at different frequencies.

The adult human has the ability to hear frequencies ranging from approximately 20 Hz to over 20 000 Hz, although the ability to hear frequencies at the top end of this scale decreases with age. Some authors have argued that the newborn hears in only a very restricted portion of this range, for example, 500 Hz–1000 Hz,⁵ suggesting a considerable expansion in the range of frequencies responded to after birth.

Observation of the fetus's response to sound stimuli do not support this as responses have been elicited by a wide range of frequencies. Responses to vibroacoustic stimuli have been observed to frequencies ranging from 83 Hz⁶ to 3000 Hz,⁷ while studies using acoustic stimulation have reported responses from 250 Hz⁸ to 5000 Hz.⁹ Most of these studies have been performed in the final weeks of gestation and illustrate that the fetus, albeit towards the end of gestation, responds to a wide range of frequencies. The range of frequency responsiveness at earlier gestations, nor how this develops, is unknown.

Early studies of thresholds for behavioural responsiveness to auditory tones in newborns revealed these to be much higher than those of adults^{10–13} and this has been confirmed by more recent studies.^{14–16} Auditory brainstem response thresholds have been reported to be higher in newborns than in adults^{17–20} and evoked otoacoustic emissions appear to grow in the first few days postpartum.²¹ This evidence indicates that newborn auditory thresholds are higher than those of adults.

Examination of the sensitivity of the adult ear to different frequencies indicates that peak sensitivity occurs around 4 kHz,²² due in part to the resonance of the external ear canal. Attempts have been made using pure tone stimuli to assess neonatal threshold levels at different frequencies. A number of studies have found enhanced sensitivity to low frequency signals (100 Hz–1000 Hz) compared with higher frequencies^{19 23 24} particularly in the region of 200 Hz–500 Hz.^{23 25} In contrast some have found no differences in sensitivity across frequencies,^{26 27} greater sensitivity to higher frequencies (3000 Hz compared with 500 Hz),¹¹ or greatest sensitivity to frequencies around 1000 Hz compared with 500 Hz and 4000 Hz.²⁸ In general the evidence suggests that newborn infants are most sensitive to frequencies in the lower part of the adult frequency range, especially below 1000 Hz,

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and their threshold levels are higher than those of adults. The sensitivity of the fetal auditory system to different frequencies is unknown.

The following experiment examined the prenatal development of behavioural responsiveness to different pure tone stimuli. Fetuses from 19 to 35 weeks of gestational age were studied and their response to different frequencies, presented at increasing levels of intensity documented. Given that hearing first develops in the lower frequency range of the adult hearing range the following study used stimuli ranging from 100 Hz to 3000 Hz, that is, the low frequency range of adult auditory abilities.

Subjects and methods

SUBJECTS

Four hundred and fifty fetuses, from singleton uncomplicated pregnancies, were studied. Subjects were obtained from the population of mothers attending the antenatal clinic at Royal Maternity Hospital, Belfast. All mothers gave consent to take part in the study. Fetuses were studied at one of nine gestational ages: 19, 21, 23, 25, 27, 29, 31, 33, or 35 weeks of gestational age. Fifty fetuses were studied at each age. All fetuses who took part in the study had an uncomplicated delivery and Apgar scores of greater than eight at one and five minutes. Furthermore, all subjects were screened for hearing problems at 8–12 months of age using health visitors' screening assessment and all were found to possess normal hearing at this time.

APPARATUS

The fetus was observed on real time ultrasound scan using an ATL Ultramark 4plus ultrasound machine with a 5 MHz scanhead. The stimuli were presented to the fetus via a speaker (AKG capsule 160, Z-61A, Z-60A) placed on the mother's abdomen. A synthesised function generator (Wavetek, Model 23), connected to the speaker, produced the stimuli used in this experiment. Five different pure tone sine wave frequencies were used: 100 Hz, 250 Hz, 500 Hz, 1000 Hz, and 3000 Hz. The intensity of the stimulus, dB(A), was measured 1 cm from the speaker face. At present there is no suitable scale for measuring intensity levels with regard to the fetus¹ and in order to provide consistency with previous studies examining fetal auditory abilities the dB(A) scale was used.

All ultrasound observations were recorded on videotape along with a visual indication of when the sound stimulus was presented and a timer to indicate time from onset of stimulus presentation. These tapes were used for later independent review by observers blind to the particular conditions (frequency, intensity) under study.

PROCEDURE

The mother was scanned while lying on a couch in a semirecumbent position with a head tilt of 45 degrees. A standard longitudinal section of the fetus was used to observe the

fetus so that the fetal head, upper body, and arms could be visualised. The position of the head of the fetus was determined and the speaker placed on the abdomen directly over the head of the fetus.

For any particular frequency, stimuli were presented to the fetus in 5 dB(A) steps of increasing intensity starting at 60 dB(A) and ending at 120 dB(A). Stimuli were presented for 2.5 seconds with an interstimulus interval of 7.5 seconds. The fetus was considered to have responded to the stimulus if it moved (head, arms, or upper body) either during the 2.5 seconds of stimulus presentation or within the immediate 2.5 seconds after cessation of the stimulus. (Such observations of fetal responses have a high interobserver reliability.²⁹) Stimulus presentation continued until either the fetus exhibited a response on two consecutive stimulus presentations or the 120 dB(A) stimulus was presented. The intensity level at which the fetus exhibited its first response, if it responded on two consecutive occasions, was recorded. If the fetus did not respond a score of 120 dB(A) was recorded but this was not used in any subsequent analysis. Fetuses were tested at one, and only one, gestational age but at that age were presented with all five frequencies and the dB(A) level at which each fetus responded was noted. Across all fetuses tested, and within each gestational age, the order in which the five different frequencies were presented was completely randomised. The first stimulus frequency was presented after a period of 120 seconds of inactivity. Presentation of each subsequent series of stimulus frequencies commenced five minutes after the end of the previous series if the fetus had been inactive for the preceding 120 seconds. If the fetus was active during the final two minutes of this five minute period presentation of the next series was delayed until a period of 120 seconds of inactivity had passed.

Results

THE NUMBER OF FETUSES RESPONDING

The first response was observed at 19 weeks of gestational age by a single fetus who responded to the 500 Hz tone. The number of fetuses responding to each frequency increased with gestational age (see fig 1). Fetuses responded first to the low frequency tones 500 Hz, 250 Hz, and 100 Hz, with 96% responding by 27 weeks of gestational age to the 500 Hz and 250 Hz tones. At this age none responded to the 1000 Hz or 3000 Hz tone. Fetuses first responded to the 1000 Hz and 3000 Hz tones at 29 and 31 weeks of gestational age respectively. One hundred per cent of the fetuses responded to the 1000 Hz tone at 33 weeks of gestational age and to the 3000 Hz tone at 35 weeks of gestation.

INTENSITY LEVEL REQUIRED TO ELICIT A RESPONSE

For those who responded to each frequency the mean intensity level at which the response was elicited at each gestational age was obtained (see figs 2 and 3). For all frequencies

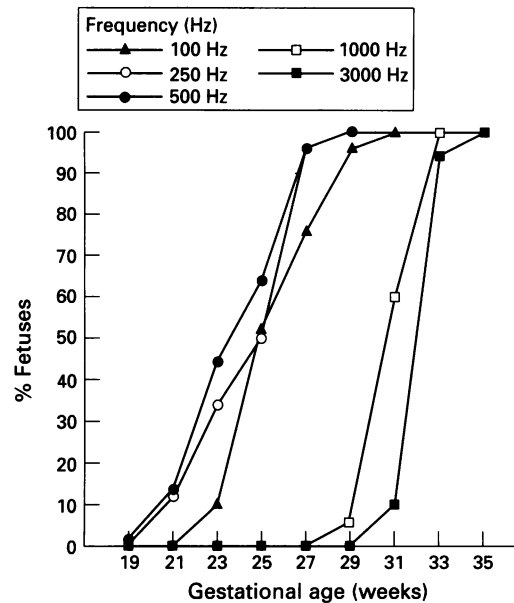


Figure 1 Percentage of individuals ($n=50$) responding to each frequency at each gestational age.

there is a significant decrease ($p<0.01$) in the intensity level required to elicit a response as gestation progressed. Lowest intensity levels were required for the low frequency tones, especially those of 500 Hz and 250 Hz. Overall as gestation advanced the intensity level required to elicit a response decreased across all frequencies.

Discussion

The results indicate that the fetus first responds to frequencies of 500 Hz and 250 Hz, that is, in the lower portion of the adult auditory range. Responsiveness to higher frequencies 1000 Hz and 3000 Hz develops later although these are still in the low-middle portion of the adult hearing range. Thus as

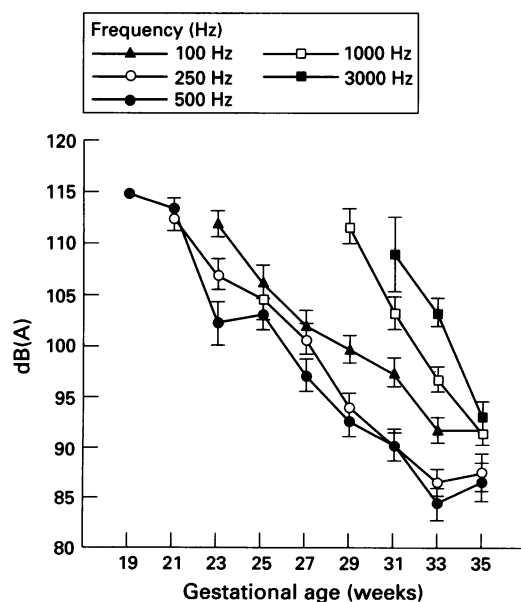


Figure 2 Mean (SE) intensity level required to elicit a response at each gestational age for each of the frequencies examined. 100 Hz $y=148.95-1.68x$; 250 Hz $y=152.38-1.95x$; 500 Hz $y=151.50-1.97x$; 1000 Hz $y=202.73-3.34x$; 3000 Hz $y=232.97-3.98x$.

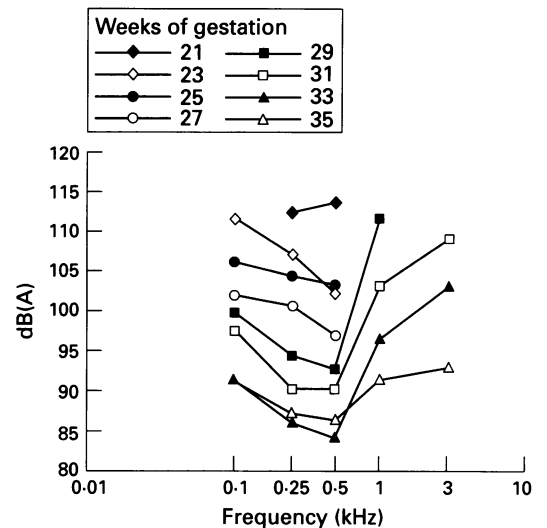


Figure 3 Mean intensity level required to elicit a response at each frequency for each gestational age.

gestation progresses the fetus exhibits a response to a wider range of frequencies. Furthermore, the intensity level required to elicit a response decreases for all frequencies as gestation increases, this may suggest that fetal hearing becomes more sensitive during gestation (fig 3). The lines for each gestational age represent the mean intensity level required to elicit a response for the fetus and may be considered as equal loudness contours. These results support previous studies examining the postnatal development of hearing which have indicated that hearing first develops in the low-middle frequency portion of the adult auditory range and that thresholds decrease with maturity.³⁰⁻³⁶

The results reported above may be used to make inferences regarding the development of auditory functioning in the fetus. However, this must proceed with caution. The maternal abdomen attenuates sound, and the level of attenuation is dependent on frequency.² Thus the externally measured sound levels do not necessarily correspond to intensity levels inside of the womb. While this factor would not change the development of responsiveness within a single frequency it may alter the relationship between frequencies and have implications for the onset of responsiveness to particular frequencies.

In order to assess the effects of attenuation by the maternal abdomen, attenuation factors reported by Querleu *et al*² were taken into account and the following values subtracted from the observed mean intensity levels required to elicit a response: 2 dB(A) at 100 Hz and 250 Hz, 14 dB(A) at 500 Hz, 20 dB(A) at 1000 Hz, and 24 dB(A) at 3000 Hz. The results of this subtraction (representing the mean intrauterine sound intensity required to elicit a response) are presented in fig 4. This figure may be more representative of the sensitivity of the ear to auditory stimuli as it more closely represents sound intensity as experienced by the fetus in utero and is hence the intensity level which elicits the behavioural response (although see later). The results of this manipulation support observations from

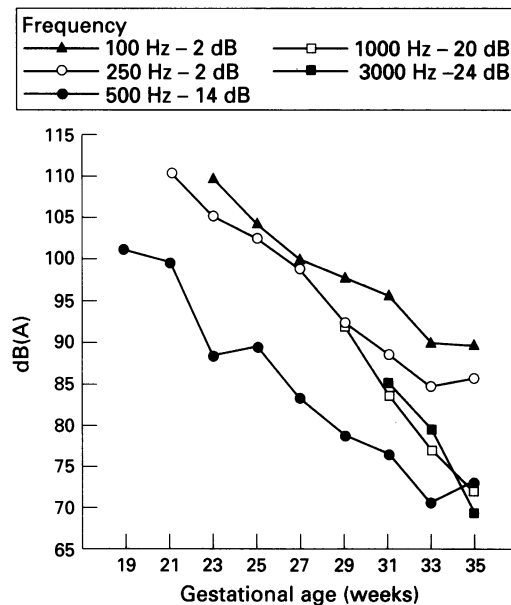


Figure 4 Mean intrauterine intensity level required to elicit a response at each gestational age for each frequency determined after accounting for the possible attenuation provided by the maternal abdomen.

data using intensity levels measured ex utero and indicate that the fetus is most responsive to the low frequency, 500 Hz, tone and that intensity levels required to elicit a response decrease as gestation progresses. They differ in the fact that the high frequency tones, 1000 Hz and 3000 Hz, now have lower thresholds required to elicit a response than the 250 Hz and 100 Hz tones, although the first response to these higher frequencies occurs later during gestation than that to the lower frequencies.

Whether accounting for the attenuation of the mother's abdomen produces results which represent the true intensity levels required to elicit a behavioural response, and indirectly information on the sensitivity of the ear, to different frequencies must be considered carefully. A number of different attenuation factors have been reported by various authors,³⁷⁻⁴⁰ those used here probably represent the best estimates at the present time, however, they are only estimates. These values were obtained during the final weeks of pregnancy, after rupture of membranes and may not be representative of attenuation with membranes intact or at earlier gestations. The attenuation factors represent only the effect of the maternal abdomen. There are a number of structural differences between the fetal ear and that of the adult which may further differentially affect its sensitivity to different frequencies.¹ Thus these results must be treated with care.

One difference between the results using intensity measured ex utero and in utero relates to the development of responsiveness to different frequencies. The fetus was observed to respond last to the frequencies of 1000 Hz and 3000 Hz. However, if the abdomen attenuates high frequencies more than low frequencies, the 1000 Hz tone, for example, presented at 120 dB(A) may in fact be only 100 dB(A) in utero which may not be intense enough to elicit a response at earlier gestations. Thus the delayed responsiveness observed to

the high frequency tones may be due to lower intrauterine intensity levels rather than any difference in the onset of auditory responsiveness to these frequencies.

One means to examine this would be to increase the intensity levels of the 1000 Hz and 3000 Hz frequencies by 20 dB and 24 dB, respectively, to counter the attenuation offered by the maternal abdomen. Ethical concerns regarding the possible harmful effects of high intensity sounds¹ on the hearing of the fetus rule out this possibility. However, two observations from the present study suggest that possible intensity differences do not account for the difference in onset of responsiveness exhibited to low frequency and high frequency tones.

First, given the reported attenuation factors of 14 dB at 500 Hz and 20 dB at 1000 Hz² it would be expected that there would be a 6 dB difference in the womb for these frequencies when of equal intensity as measured outside of the womb. Assuming that frequency responsiveness to the 500 Hz and 1000 Hz tones develops at the same time it would be expected that there should be a difference of 6 dB in the responsiveness to these tones. However, this is not the case, differences of 19.1 dB, 13 dB, 12.5 dB, and 5 dB in responsiveness at 29, 31, 33, and 35 weeks of gestational age were observed. Only at 35 weeks is the difference in intensity level required to elicit a response approximately 6 dB, at earlier ages the difference is 2-3 times greater. These results suggest that intensity differences due to differential attenuation of high and low frequencies do not solely explain the earlier behavioural responsiveness of the fetus to the 500 Hz tone over the higher frequency tones.

Second, if the response of the fetus to different frequencies differed only because of the intensity differences it would be expected that the increase in responsiveness with gestation would be equal for all frequencies. This is not the case. Although all frequencies exhibit a highly significant decrease in intensity level required to elicit a response, the slopes of the decline are different for different frequencies. Observation of fig 2 indicates that the 1000 Hz and 3000 Hz tones show a steeper decline in intensity level required to elicit a response than the 100 Hz, 250 Hz, and 500 Hz tones. For the two higher frequencies the decline in intensity level required to elicit a response for the 3000 Hz tone appears slightly faster than for the 1000 Hz tone. The decline in intensity level required to elicit a response for the three lower frequencies appears visually similar. In order to determine whether these visual observations were correct a statistical analysis⁴¹ was performed to compare the slopes of the decline in intensity level required to elicit a response for each frequency. For this the difference in observed threshold for each fetus that responded to each pair of frequencies (for example, 100 Hz-250 Hz, 100 Hz-500 Hz and so on) was obtained and regressed against gestational age. The resulting slopes were then compared against zero using a *t* statistic.⁴¹ The results of these statistical tests (table)

Table of results obtained from comparing the slopes of lines produced by auditory threshold data for each frequency

Frequency					
Frequency	100	250	500	1000	3000
100	—	$t=0.37$ df=264 NS	$t=1.10$ df=265 NS	$t=9.40$ df=131 $p<0.0001$	$t=8.58$ df=100 $p<0.0001$
250	—	—	$t=1.42$ df=288 NS	$t=4.69$ df=131 $p<0.0001$	$t=5.34$ df=100 $p<0.01$
500	—	—	—	$t=6.83$ df=131 $p<0.0001$	$t=7.31$ df=100 $p<0.0001$
1000	—	—	—	—	$t=3.32$ df=100 $p<0.01$
3000	—	—	—	—	—

confirmed observations made from the graph. The decline in intensity level required to elicit a response for the three lower frequencies (100 Hz, 250 Hz, and 500 Hz) was not significantly different from one another but for all three frequencies was significantly different from the decline in intensity level required to elicit a response for the two higher frequencies (1000 Hz and 3000 Hz). Furthermore, there was a difference in the slopes of the decline in intensity level required to elicit a response for the two higher frequencies (1000 Hz and 3000 Hz). These results suggest that intensity differences are not solely responsible for the difference in the onset of responsiveness observed to different frequencies.

In summary, although the maternal abdomen will differentially attenuate different frequencies, the developmental differences observed in responsiveness to these frequencies may represent true differences in their maturation. The range of frequencies responded to widens as the fetus ages. The intensity level required to elicit a response decreases with advancing gestation. When sound intensity is measured *ex utero* the fetus is most responsive to the 500 Hz tone and below. When using intensity assessed *in utero*, the fetus may be more sensitive to 500 Hz tones and above. The results indicate that fetal response to sound commences in the lower parts of the adult frequency range and expands its frequency range and increases in sensitivity as the fetus matures.

IMPLICATIONS FOR THE DEVELOPMENT OF THE FETAL AUDITORY SYSTEM

As mentioned previously examination of fetal auditory abilities may only proceed indirectly at present, via the observations of behavioural responsiveness to sound. After birth auditory threshold levels obtained by observations of behavioural responding are higher than those obtained by more direct means, for example, auditory evoked brainstem responses.¹⁸ Thus the findings obtained here cannot be used to assess absolute thresholds. However, the observations of behavioural responding may provide information regarding the development of auditory function.⁴

The responses of fetuses of different gestational ages to the acoustic stimuli used in this experiment indicate two aspects of auditory

function which develop from 19–35 weeks of gestation. First, the fetus begins hearing in a restricted range of the adult's frequency range, around 500 Hz and this range expands during the course of development. Second, the initial responses elicited by a particular frequency require an acoustic stimulus of greater intensity than later during gestation, indicating that fetal hearing becomes more sensitive during development. The intensity levels of stimuli required to elicit a response at 35 weeks of age is 20–30 dB less than when the fetus first starts to respond. Observations of premature infants reveal a 20 dB decrease in the intensity level required to elicit an auditory evoked brainstem response from 28–34 weeks' gestational age to term.⁴²

This development of auditory responsiveness suggests a parallel development in the auditory system. The cochlea commences development around 10–12 weeks of age and it has been estimated that the mechanical functioning of the cochlea, except for the most basal part, is mature by 30–35 weeks of gestational age.⁴³ The developmental changes observed here thus reflect underlying changes in the auditory system occurring between 20–35 weeks of gestation.

One important development around this time is the innervation and completion of the outer hair cells which are responsible for turning the basilar membrane into an active transducer of acoustic stimuli rather than simply a passive one. The possible role of this for the development of the hearing frequency range, or the increase in sensitivity, is unknown.

While it is undoubtedly true that the periphery sets the limits on what can be processed, the development of fetal hearing must also be affected by the development of the auditory nervous system and this too may influence the increased responsiveness observed in this experiment. For example, the development of the ventral cochlear nucleus accelerates between 18–33 weeks of gestational age⁴⁴ and this may play a part in the development of auditory responsiveness.

The changes in behavioural responsiveness observed in this study correlate with changes observed in auditory brain stem responses from premature infants of similar ages. From the initial reliable recordings of the auditory evoked brainstem response in premature infants at 28 weeks' gestational age, wave amplitude increases, wave latency decreases and interwave interval decreases with advancing age, until approximately 2–4 years of age when 'mature' values are recorded.⁴⁵ Of particular interest is the observation of a rapid reduction in interwave response latency between 28–36 weeks of gestation, a reduction which slows over the next 1–2 years. The underlying mediation of this, argued to be the result of maturation of the brainstem leading to decreased brainstem conduction times, possibly due to greater synaptic efficiency, may play a part in the observed changes in fetal responsiveness.

The finding of initial low frequency responsiveness corresponds to other behavioural and

physiological findings which indicate that the developing auditory system responds first to low frequency sounds.⁴⁶⁻⁴⁸ The frequencies used in this experiment, with the exception of the 3000 Hz tone, would in adults be encoded by the volley principle, that is, the firing rate of the auditory nerves would match that of the stimulus. The 3000 Hz tone falls in the region where both the volley and place principle would operate and thus both mechanisms may account for encoding this frequency. However, whether, at this early developmental stage, the place and volley principle work at the same frequencies as observed in adults is unknown.

Given that the frequencies used are, in adults, encoded in the firing pattern of the auditory nerves, the developments in responsiveness may be a result of the development of the auditory nerves and their firing rate. Of particular interest is the apparent difference between the 100 Hz, 250 Hz, 500 Hz tones and 1000 Hz and 3000 Hz tones in the gestational age at which the fetus first responds and their different rates of sensitivity change. The firing rate of auditory nerves is about 1000 impulses per second, set by the refractory rate of the nerves. Thus tones below this may be encoded in the firing pattern of a single nerve, but above this nerve fibres have to act together, phase locked firing to encode the stimulus.⁴¹ It may be that the difference observed here between tones below 1000 Hz (100 Hz, 250 Hz, 500 Hz) and tones 1000 Hz and above is due to the development of the volley principle and phase locked firing enabling groups of nerves to act together.

There are thus a number of maturational developments of the fetus's auditory system which may account for the increased range and sensitivity of hearing observed in these experiments, although the actual mechanism remains unknown at this stage.

FUNCTIONAL IMPLICATIONS

The behavioural response of the fetus develops first to frequencies around 500 Hz and lower and the fetus is more responsive to these frequencies than to high frequencies. This will have implications for the fetus's response to auditory stimuli generated in the external environment. The sensitivity of the fetus to low frequency sounds means that the fetus will be exposed to sounds of speech and language. The fundamental frequency of the human voice is around 225 Hz for females and 128 Hz for males and thus the voice will form a salient auditory stimulus for the fetus. It is known that the fetus recognises its mother's voice from prenatal exposure⁵⁰⁻⁵² and is able to discriminate between different speech sounds in utero.⁵³⁻⁵⁵ This exposure to speech may be important for the development of language³ and for recognition of the mother and development of attachment.⁵⁶ The frequencies to which the fetus first responds are those which are relatively unattenuated by the maternal abdomen and thus will perhaps be 'loudest' in the womb, increasing their saliency.

The increased responsiveness of the fetus to

low frequency sounds is also of importance when considering the possible harmful effects of sounds on hearing.¹ For a broad band sound of equal intensity ex utero the low frequencies will pass relatively unattenuated into the womb. As these sounds correspond to the frequency range in which the fetus first responds to sound, low frequencies may be potentially more harmful to the developing ear of the fetus than high frequency sound.¹ Care should be taken to avoid intense exposure to low frequency sounds.

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